UCRL- 91531
PREPRINT

THE POWER OF DETERMINISTIC THINKING IN MACHINE TOOL ACCURACY

James B. Bryan

This paper was prepared for submittal
to the First International Machine Tool
Engineers Conference, Tokyo, Japan
November 7-8, 1984

September 1984

Lawrence Livermore National Laboratory

THE POWER OF DETERMINISTIC THINKING IN MACHINE TOOL ACCURACY

James B. Bryan

Lawrence Livermore National Laboratory
P. O. Box 808, L-332, Livermore, California 94550

Abstract

Philosophy is an important factor in precision engineering in general and the upgrading of machine tool accuracy in particular. Our philosophy has evolved from the history of the field, our own experience and the advice of colleagues. The main elements of this philosophy are the importance of patience, continuity of effort, good measuring equipment, good temperature control, carefully designed tests, and belief in the idea that machine tools obey cause and effect relationships that are within our ability to understand and control and that there is nothing random or probabilistic about their behavior.

Preface

It is indeed an honor to be invited to participate in this first International Machine Tool Engineers Conference. In preparing for this occasion, I found an unpublished article that I had written in 1971 describing the philosophy that we had adopted to guide our work on machine tool accuracy. I had originally intended to rewrite and update the article for presentation at this conference. I have since decided to present the original version intact and simply add an Appendix consisting of additions, comments, and quotations from other people. The reason for this decision is that the original article has the virtue of being short, reasonably complete, and has withstood the test of time.

Introduction

Lawrence Livermore National Laboratory (LLNL) has been involved in the upgrading of machine tool accuracy for the past twenty years. We think we have been reasonably successful in this effort, and are pleased at any opportunity to share our experience with other people. Success in this field requires a combination of ingredients.

There is a need for skilled and dedicated craftsmen, sympathetic management, good measuring equipment, purposeful and believable goals, continuity of effort, patience, and finally, some kind of underlying philosophy to provide guidance through the inevitable periods of confusion and discouragement. This paper deals with our philosophy.

Our philosophy has evolved from three different inputs: (1) history of the field, (2) our own experience, and (3) advice of colleagues. History has taught us the virtue of patience, simplicity and attention to fundamentals. Experience has taught us the power of positive (deterministic) thinking. The advice of colleagues throughout the world has put our experience into perspective.

History as an Input to Philosophy

Machine tool accuracy is covered under the general field of engineering dimensional metrology (precision engineering). The field has a history of early accomplishment that is amazing. In 1865, for example, SIP (Societe Genevoise D'Instruments de Physique) developed their first linear dividing machine equipped with a lead screw corrector bar. By 1924 they were able to guarantee an accuracy of plus or minus 80 microinches in a travel of 40 inches. The field began to take shape as an engineering discipline in 1899 with the invention of the Johansson gage block by C. E. Johansson[1]. The mechanism by which "Jo" blocks stick together and exhibit up to 480 pounds per square inch of attractive force became the subject of intensive study and discussion by European physicists. Dr. R. H. Rolt, Director of the National Physical Laboratory in England, documented the results of these studies in his book, "Gauges and Fine Measurements" published in 1929.[2] The thickness of the wringing film between the blocks became the subject of a particularly heated debate. The French physicist Perard claimed that the film was negative by 2-1/2 microinches because of compression of the surface asperities while Rolt and his team at NPL claimed a positive thickness of .3 microinch. Current data on the question supports Rolt. Very little improvement has been made on the exquisitely simple series of experients that Rolt used to make the measurement.

Gage block technology is only a part of Rolt's book. He covers all aspects of metrology including optics, air gages, capacitive gages, inductive gages, interferometry, line standards, material instability, thermal effects, design of measuring machines, and instruments of all kinds. In my opinion, 90% of our present day technology is covered in this book.

I have had the privilege of several interviews with Dr. Rolt. I remember asking him why he was concerned about a few tenths of a microinch at a time when there was no application for such accuracy. He replied that his conscience bothered him when he signed the official certificates of measurement stating an accuracy level he couldn't be quite sure about.

Reading Dr. Rolt's book is a very humbling experience. To me, it represents hard evidence that dimensional accuracy is on the flat part of the maturity curve and not characterized by breakthroughs or multiple order of magnitude improvements. Bicycle design is another technology which is on a relatively flat maturity curve. Bicycle efficiency, as measured by the ratio of load carrying ability to human energy required to achieve a given speed, has improved by less than 10% in the past 50 years.

The above reasoning does not mean we wouldn't like to have some breakthroughs, that they will not occur, or that we are not looking for them. It just means that we should be skeptical about depending on them for advancement (Appendix 2). Progress will more likely be achieved by step-by-step attention to the fundamentals. On the positive side, a great deal of progress has been made in transferring the laboratory techniques described by Rolt to the shop floor. We are happy to share some of the credit for this accomplishment.

When compared to advancements made in other fields (astronautics, aeronautics, computers, electronics, lasers) in the same time period, however, we look pretty bad. There is a consequent tendency on the part of outside observers to think that something is wrong with the approach. This generally leads to suggestions that the approach be more exotic. Our interpretation of the history of the field indicates, however, that exotic methods should be the last resort and that the simplest possible solution is the best in the long run.[12]

History also tells us something about the need for patience and continuity of effort in this work. The SIP Co., for example, spent fifteen years in developing their first photo-electric microscope. Another example is that of the Moore Special Tool Co. in Bridgeport, Connecticut which has spent over 30 years in perfecting the design of their precision leadscrew. The history of diffraction grating ruling machines at Bausch and Lomb in Rochester, N.Y., indicates that 10 years is not unusual for the development of a new machine.

LLNL Experience as Input to Philosophy

The term "positive thinking" has been coined to express a special viewpoint about mechancial accuracy that has developed at LLNL over the years. We use the terms "deterministic thinking" and "brute strength approach" interchangeably.

The basic idea is that machine tools obey cause and effect relationships that are within our ability to understand and control and that there is nothing random or probabilistic about their behavior. Everything happens for a reason and the list of reasons is small enough to manage.

The statisticians call this a deterministic situation. Very few people believe that machine tool accuracy falls in this category [6][7] (Appendix 5). We believe it, probably because we have a special insight brought about by very special circumstances (Appendix 3). We have had the benefit of good people, good management, good measuring equipment, purposeful goals, continuity of effort and patience. Not many organizations can claim such a combination (Appendix 3).

The most important step in our self-education process regarding machine tool behavior was the early use (1955) of electronic indicators and strip chart recorders instead of mechanical dial indicators. Electronic indicators provide the sensitivity, and the recorders provide the memory necessary to discover the remarkable, but usually hidden, repeatability of motion of machine tools.

These instruments allowed us to identify thermal effects as the largest source of apparent non-repeatability[14][15]. When the nature of this influence was fully understood we were able to bring it under control[10]. The other sources of apparent non-repeatability are sliding oil films, sliding friction, loose joints, dirt, change of position of rolling elements, and vibration. We use the term "apparent" non-repeatability because each influence is in itself repeatable if the conditions affecting it are repeated.

Take for example, the behavior of a pre-loaded ball bearing spindle. If the successive positions of the spindle are recorded at each full revolution, a pattern of non-repeatability develops due to the precessing of the imperfect balls with respect to their races. This pattern will superficially appear to be totally random and confused. A statistician would be strongly tempted to assume a random process with a Gaussian distribution and begin calculating values for x- bar, sigma and probability. If the spindle is reversed, however, the position plotted for each revolution going backward will be a mirror image of itself going forward. If this is the case, it is clear that there is nothing random or probabilistic about the system at all. It is totally deterministic and can be upgraded by the brute strength, positive thinking approach of simply using better balls and races in the bearings. Good measuring equipment and discipline is the key to this discovery. We would be denied this information if we were using a sticky indicator with a loose tip or a weak bracket, had poor temperature control, did not rotate the spindle a full revolution each time, had a rough finish or dirt on the spindle indicating surface, did not record the data in its proper sequence, or simply believed in witchcraft.

Throwing Dice

If the above logic is extended a bit, it might seem that there is no such thing as a truly random process. It is not unreasonable to think that there are specific reasons why dice behave as they do when thrown. Their initial position, force and direction of throw, conditions or rebound, etc., all determine the end result in a deterministic way. Because of the large number of variables and the negative incentive to measure and control them, the process <u>appears</u> to be random.

Professor Loxhom's Philosophy

In developing our thinking along these lines, I had an occasion to discuss the question with my colleague, Prof. Loxham of Cranfield University. Prof. Loxham is a man of many talents. He is an astronomer, machine tool and instrument designer, metrologist, manager and investor. I was quite happy to discover that Prof. Loxham agreed with our thinking and had written a paper on the subject. It is entitled "The Commerical Value of Investigations into Repeatability."[3] He makes the following observation:

"A very rigorous mathematical and experimental analysis into a wide range of natural laws establishes the remarkable fact that 'there appears to be no known error in any natural law.' These laws are therefore 100% perfect, unchanging and in consequence very reliable. Industry in general has not recognized the benefits that can be obtained by exploiting these 100% perfect and very reliable natural laws as they operate in the engineering workshop. A close study of an automatic manufacturing process shows that it is operating under the influence of natural laws and is not affected by the very wonderful, complicated, but slightly unpredictable mechanism known as a human being. If, as indicated above, all natural laws operate with 100% perfection, an automatic manufacturng process could be classified as operating perfectly. It may not be doing what is required, but if that is so it is because it has not been suitably arranged."

Some people have reacted to this quote with the comment that there is no such thing as 100% perfection and no such thing as a "natural" law. Such laws are just models made by man to help him understand natural phenomenon. I have discussed these conflicting viewpoints with Dr. Ray Kidder of the Theoretical Physics Department at LLNL. According to Dr. Kidder, both views can be considered partially correct. The classical laws of Physics break down when very small masses, such as electrons, are involved. The theory of Quantum Mechanics is then required to explain the stability of the atom. Quantum Mechanics is fundamentally probabilistic as distinguished from the deterministic nature of classical Physics. Planck's Constant determines the scale involved when Quantum Mechanic considerations must be taken into account. The product of the uncertainty of momentum times the product of uncertainty of position is equal to Planck's constant which is on the order of 10^{-27} erg-secs. This is sometimes called Heisenberg uncertainty. For engineering and even astronomical purposes where classical objects are being studied, such a small value can be considered zero since the present day accuracy of the standards of time, mass and length are on the order of one part in 10^{10}. Prof. Loxham's statement concerning 100% accuracy and the deterministic nature of classical physics can therefore be considered correct when we are dealing with masses much larger than a molecule.

According to Dr. Kidder, there are two other phenomena besides the stability of the atom which presently require a probabilistic explanation. These are Brownian movement [11] and shot noise. Brownian movement is a thermal noise effect influencing the motion of small particles after random collision with molecular particles. Its magnitude is determined by Boltzman's constant which is on the order of 10^{23} joules/degree. Shot noise is observed in the behavior of very small current flows. The current becomes discontinuous because it is made up of randomly spaced, discrete electrons. The magnitude at which this phenomena occurs, however, is on the order of 10^{-19} amperes.

If classical physical laws are deterministic, we can see that the probabilistic approach to a problem is only a tool to allow us to deal with variables that are too numerous, or expensive to properly sort out by common sense and good metrology. There is, of course, nothing "wrong" with this approach except that it may lead to an implicit assumption about the necessity of ignorance.

The above discussion gives the background leading to the philosophy that we have adopted to guide our work on machine tool accuracy. It can be approximated by the following set of rules:

1. Don't depend on breakthroughs. Identify the weakest link in the system and concentrate on upgrading it.

2. Be patient, it takes time to sort out the variables, but it can be done and the rewards are worth it.

3. Keep design solutions as simple as possible.

4. Don't assume anything, measure with good equipment and carefully designed tests.

5. Don't use statistics indiscriminately, they are generally not necessary for the limited number of variables in a machine tool.

6. Suspect temperature, dirt, loose joints, and friction as the most likely sources of apparent non-repeatability.

7. Keep Loxham's law in mind. "An automatic machine is always operating perfectly. It may not be doing what is required, but that's because it isn't suitably arranged."

8. Remember that "random results are the consequence of random procedures."

APPENDIX

ADDITIONS, COMMENTS AND QUOTATIONS FROM OTHERS

1. Rule #8

Another conversation with Professor Loxham on determinism, in 1977, included Mr. Jeff Portas, Chief Electronics Engineer, at CUPE. Mr. Portas listened to the discussion very quietly and finally made a remark that I will never forget. He said that in his experience, "random results are the consequence of random procedures". This quote has since become Rule #8, which is listed above for the sake of completeness. It was obviously not in the original paper. It is one of my favorite quotes because it says so much in so few words.

2. Breakthroughs

In the process of rethinking and extending the ideas laid out in the original paper, I came across an article entitled, "Technology Development" by Ralph Gomory, Vice President of IBM and Director of Research. It was published May 6, 1983 in Science magazine.[4] I have never met Mr. Gomory but I was absolutely delighted to find that such an important person agreed with our ideas on breakthroughs and the roles of science, technology and culture and, more importantly, was able to express them so clearly. It is not surprising then, that I quote Gomory extensively in the following pages.

Mr. Gomory says that: *"Technology Development is much more evolutionary and much less revolutionary or breakthrough-oriented than most people imagine. It is important to realize that a series of evolutionary steps in technology, together amounting to a large improvement, is just as revolutionary as a breakthrough. That this is the normal course of technology development may be illustrated by two (2) historical examples.*

<u>Evolution of the Steam Engine</u>

"The first example is the invention and development of the steam engine. The Dutch physicists Christian Huygens and Denis Papin conceived the idea in 1680 and built the first working model in 1690. Thomas Newcomen, an English plumber, built the first reliable and widely used engine. It found its first application in pumping water out of coal mines. The Newcomen engine had an efficiency of 4 million ft-lbs of work per bushel of coal. A horse can produce about 20 for the same cost. In 1767, John Smeaton, a machinist, raised the efficiency to 12 by boring the cylinders to a closer tolerance. Finally, in 1775 James Watt, an instrument maker and the inventor of the first micrometer, raised the efficiency to 30 by adding an external condenser and a two-stroke cycle. Multiple expansion cylinders and high pressure steam have since raised the efficiency by another factor of 4 to 120 which is its present day value. It took three centuries to evolve a factor of 30. "One of the morals of history is that the people who did the work (technology development) were plumbers, wheelwrights and instrument makers.

<u>Evolution of the Digital Computer</u>

"The second example of evolution is the computer. Charles Babbage, an Englishman, conceived the idea of a programmable computer more than 100 years ago. Vacuum tubes were used extensively in the first practical computers but the invention of the transistor revolutionized the field. The transistor was a real breakthrough. It was the result of a long buildup of understanding of solid-state physics and then a rather sudden transfer of that knowledge into a new area - the area previously populated by vacuum tubes. Once it got going, this development, like the steam engine, was in the hands of practitioners. It was mentioned before that the evolution of the steam engine was conducted by mechanics, plumbers, and so on. Similarly, the transistor came out of fundamental scientific knowledge, but its continued development was in the hands of semiconductor engineers, where today it is evolving rapidly.

"Real breakthroughs do occur; they are rare and stunning events. The more common course of technological evolution is steady, year-to-year improvements, and when that is rapid and persistent, the results are just as revolutionary.

Science and Technology

"Armed with these histories of the steam engine and the computer, we can raise questions about science and technology. How do they interact? The two examples cited indicate that it is a two-way street and that science and technology affect each other, and are affected by each other, in more than one way. Of course, we are accustomed to the idea that science contributes to technology. The early history of the transistor is an example of the introduction of scientific knowledge into technology with stunning results. On the other hand, the development of the steam engine was the work of practical men gradually adding improvements driven by the needs of application. This persisted until the 1830's, when the need to make still better steam engines and to understand them stimulated the development of the science of Thermodynamics. Technology in that case drove fundamental science. This is happening today; the computer is driving computer science. Furthermore, the evolution of technology makes better scientific instrumentation possible, and this can be a major factor in the advancement of science.

"Scientific research is motivated by the desire to satisfy curiosity, as opposed to the imperative of technology to get out a working product.

"In the United States, science (in contrast to technology) is highly valued. Scientists are esteemed more than the practitioners of technology. The current relative prestige of science and technology is peculiarly American. The situation varies a great deal from country to country, and in some countries it is considerably different from that in the United States."

Breakthroughs in Precision Engineering

In my opinion, there have been only two breakthroughs in Precision Engineering in the past 100 years. The first was the invention of the gage block by C. E. Johansson in 1899. This development was not the result of science. Just the opposite was the case. The gage block forced the scientific community to explain the reason for the 480 pounds per square inch attractive force. The scientific effort that followed became the foundation of Precision Engineering. Some of this work is documented in Dr. Rolt's book "Gauges and Fine Measurements" mentioned earlier. I think this relationship is analogous to the steam engine forcing the development of Thermodynamics.

The second breakthrough in Precision Engineering was the laser and the laser interferometer. The laser was the result of basic science and came from another field. As the transistor drove computer technology, the laser interferometer is now driving machine tool technology.[13][16]

3. Cultural Factors

In the original paper I spoke of the special insight brought about by the special (cultural) circumstances that we have had at LLNL. Mr. Gomory addresses this point as follows:

"In dealing with technology, things are sufficiently complex that much is done by rule of thumb and not by precise knowledge. Many factors enter in; some of them are even cultural. (I am using the word culture here only to indicate a general set of habits of a group of people. There is no implication that this culture is unchangeable; in fact, it is very changeable.) Let us consider an example. A complex part was being made. It went through a large number of process steps. Only about six (6) percent of the parts that came out at the end worked. That was not nearly enough because, with the cost of the whole process, a six percent yield made the parts too expensive. On the other hand, no one could find anything seriously wrong with the process. So the engineers moved in and stood where the production people had been, and they carried out the process in the hope of finding out where it was going wrong. They never found anything wrong; because they got a yield of approximately 60 percent when they did exactly the same thing! Eventually it became clear that the people who had been doing the processing simply had not been trained to be precise enough. Sometimes they put a screw-driver in a hole that was later used for precise positioning. In handling a part they sometimes made little nicks and scratches on it or touched it with their hands. Later, things would not adhere to the surface that had been touched. The accumulated effect of those things made the difference between 6 and 60 percent.

"Technology is culture-dependent in other ways. Cultural factors such as attitudes toward financing (long-term versus short-term goals), attitudes toward carelessness and small mistakes (quality), and the presence or absence of the famous NIH (not invented here) syndrome (it is hard to get someone else's idea into your laboratory) have a tremendous influence on technological progress.

"This picture of technology as a complex and even culture-dependent process bears on a number of things, including security, in the sense of secrets; and technology transfer, in the sense of trying to get a technology to someone else in the same country or in other countries.

"It is hard to keep a simple idea secret. The idea, for example, of having a separate condenser for a steam engine can be expressed in one sentence. It is hard to keep that one sentence a secret. On the other hand, it is hard to transfer the full complexity of a technology. There is too much. Those who are not technologists in the same field cannot even be sure which details matter. So simple things are hard to keep secret, and complex things like technology are hard to give away."

4. The Discovery of the Planet Neptune

In May of 1981, I had another discussion with Professor Loxham on the subject of reliability of natural laws and the deterministic approach to machine tool accuracy. Professor Loxham suggested that the story of the discovery of the planet Neptune in

1846 might illustrate the ever present temptation of researchers to disregard fundamentals and make up wild theories to explain experimental evidence that is unusual.

"The story of the tracking down of Neptune is among the most remarkable in the history of astronomy and of science.

"It all arose from the irregularity of the motion of the planet Uranus. Accurate observations often have a future importance quite unrealized by the observer. So it was with the first nineteen records of Uranus's position, made at dates between 1690 and its official discovery by Herschel in 1781.

"Within their limitations, all the pre-discovery observations were sound: their accuracy was vindicated by Bessel in 1840. They should have been extremely useful because, extending over so many years, they gave widely separated points on Uranus's path. This should have enabled the elements (basic dimensions) of the orbit to be so well determined that future positions of the planet could be accurately predicted. Unfortunately when A. Bouvard came to work out the elements, making due allowance for the pulls of Jupiter and Saturn on Uranus, he could not find an orbit into which both the early observations and those of 1781-1820 would fit even approximately. Thus he had to base his tables of Uranus (published 1821) on the later observations alone. He suggested that the impossibility of reconciling the two sets of positions might be due either to inaccuracy of the earlier ones, or to some unknown influence on the planet.

"As time went on the situation steadily worsened. Observatons after 1820 showed Uranus falling farther and farther behind its predicted places. In 1837 G. B. Airy, the new Astronomer Royal, wrote: 'The errors of longitude are increasing with fearful rapidity.'

"No longer able to blame the early observations for the continuing misbehaviour of Uranus, Airy was inclined to suspect errors in the calculation of the orbit, and even to share, with a few other astronomers, doubts whether the law of gravitation was absolutely correct at such great distances from the Sun.

"Wilder theories were proposed at this time: a resisting medium; an undetected satellite; a collision with a comet. But no one could explain why a resisting medium should afflict Uranus and no other planet; how a large massive satellite could possibly have gone undetected; or how it or a collision could continue to slow down the planet's motion.

"By 1845 Uranus was out of place by the 'intolerable quantity' of two minutes of arc, enough to darken the lives of astronomers and mathematicians. Yet the dawn was at hand.

"The solution to the mystery was based on the calculations of two (2) young mathematicians, John Adams, an Englishman, and J. LeVerrier, a Frenchman. Working independently, but with faith in Newton's law of gravitation,

they calculated the mass, orbit and position of an undiscovered plant whose influence would explain the strange behaviour of Uranus. The calculations and explanations thereof took three (3) years, but when a telescope at the Berlin observatory was finally pointed at the predicted location in the sky on the night of September 23, 1846, the planet Neptune was there!"

5. Statistical Description of Machine Tool Nonrepeatability

Statistical description of machine tool nonrepeatability is a popular idea. A committee of the National Machine Tool Builders Association in the U.S.A. has agreed on a set of Definitions and Evaluation Procedures for Accuracy and Repeatability of Numerically Controlled Machine Tools (August, 1972). This document defines nonrepeatability as "*the expected three sigma dispersion on each side of the mean resulting from a series of trials when approaching a given point under the same conditions*". It goes on to say that "*In general, any movement of a numerically controlled machine results in a final position randomly dispersed about a mean. The amount of dispersion results from several factors but exists because the system has some deadband, however small, in which the control is satisfied and no further call for motion is made.*" Similarly, the Metrology Committee of CIRP has issued a 1978 report on Defining and Specifying the Dimensional Unretainity of Multi-Axis Measuring Machines. This report defines random errors as "*those which under apparently equal conditions at a given point do not always have the same value and can only be expressed statistically*".

As a dedicated believer in the deterministic approach, I have always disagreed with the treatment of nonrepeatability in these documents. My reason for disagreement is their assumption that nonrepeatability has a fixed value for a given machine and is fundamentally random. The authors of these documents are all highly qualified people, however, many of whom are close friends and respected colleagues. Some of them are here today. It seems appropriate on this occasion that I should try to state the deterministic position as clearly as possible in the hope that our differences can be narrowed.

1) A determinist will never agree that a fixed value of nonrepeatability can be assigned to a given machine. Such a value does not exist. Nonrepeatability depends primarily on the time, money, and skill (culture) of the user.

2) A determinist will be happy to agree that some level of apparent nonrepeatability does exist for a given machine, on a given day, for a given series of tests, programmed in a given way, conducted by a given person, in a given environment consisting of a given level of temperature variation, vibration and dirt, using a given set of instruments with a given limitation on time and money.

3) A determinist might also agree that the assumption of a Gaussian distribution and the calculation of sigma values, although technically invalid, might be useful as

a statement of the level of the above variables existing at the time of a test.

4) A determinist will have great doubt and anguish in ever agreeing that some level of nonrepeatability is inevitable regardless of the time, money, and skill available. This issue is negotiable, however.

Comment on Point #3: A determinist would not want to waste the time necessary to make enough runs to calculate a three sigma value. He would first make a hysteresis test, and then a thermal drift test. He would then make a sufficient number of repeat-abiliity runs to determine that the range of nonrepeatable values is compatible with the resolution and quality of the machine and the time and money available. If not, he would stop and fix the problem. He would then proceed to measure the systematic errors concentrating on finding the worst points as soon as possible. If the systematic errors are close to the tolerance level, he might make additional repeatability runs at those points.

Comment on Point #4: In reference [8] (1972) Dr. R. Donaldson at LLNL made the following observation: *"It might be argued from a philosophical point of view that at some level of accuracy one will be faced with random and uncontrollable variables which will require statistics, but we have found as a practical matter that this is not a problem clear down to the microinch level of accuracy."* I discussed this quote with Dr. Donaldson last September and asked him if he would now (1984) be willing to change this quote to *"not a problem down to the tenth microinch level"* and he readily agreed.

Prof. N. Taniguchi in Ref. [16] (1983) says that *"Today, ultra-precision machining means the achievement of dimensional tolerances in the order of 0.01 micrometer (approximately 0.5 microinches). The resolution and repeatability of such machines must be in the order of .01 micrometer."* I have not discussed the issue of determinism with Prof. Taniguchi, but I look forward to the possibility of doing so on this trip. I notice with great satisfaction, however, that Prof. Taniguchi associates resolution with repeatability on a one-to-one basis. Such a linkage is the trademark of a dedicated determinist.

6. Statistical Description of Systematic Errors

A relatively noncontroversial question arises as to the proper treatment of systematic errors such as displacement, straightness, squareness, etc. The NMTBA and CIRP documents both evaluate systematic errors on a "worst point" basis. The new American Standard ANSI B89.1.12 on "Performance Evaluation of Coordinate Measuring Machines" specifically states that "the worst points are to be measured as often as necessary to establish the existence of a systematic error". This practice is in accordance with industry tradition and should be continued. The reason is that in most engineering projects no credit can be given for good work. If a bridge collapses there is no appreciation for the elements that did not fail. A similar argument applies for pressure vessels, engine components, and quality sensitive goods of all kinds. It is reasonable to buy and sell on the worst points. There are a few exceptions to this rule. In optics, for example, an RMS evaluation of form accuracy makes good sense.

7. Statistics in Quality Control

The overall quality of Japanese goods is admired throughout the world. A natural question arises as to "how they do it." Many theories are offered. An increasingly popular theory in the United States is that Japanese quality is achieved by statistical quality control. If that is true, we should simply hire more statisticians and our quality problems will be over.

I do not believe this theory. In preparing this paper, I have discussed the question with dozens of experienced production engineers from many different countries. No one that I talked with believes the theory. It didn't seem to matter if the production rate was one a year, or two million a year. Good quality has many crucial factors [17], but in my experience, and that of my trusted colleagues, statistics is not one of them.

I look forward to the possibility of further discussions on this question with representatives from industry in Japan who obviously have the real answer.

8. Statistics in Medical Research

Statistics can be a powerful tool in narrowing the number of variables in very complex research problems. In the medical research field, for example, statistics are indispensible. I have discussed this subject with Dr. Max Biggs, my friend and neighbor for the past 25 years. Dr. Biggs is now retired, but he was the Chief Medical Officer of LLNL for 30 years. In addition to his medical degree, he has a Ph.D in in Medical Physics, and is an expert in statistics. He has been closely involved with cancer research. Dr. Biggs diagnosed a total of 30 cases of skin cancer (melanoma) during his career at LLNL and showed that this was apparently a higher than normal rate. Establishment of a <u>normal rate</u> for a given population in a given area is a non-trivial statistical problem. An important variable is the standard used in measuring (diagnosing) the disease. As mentioned earlier, good metrology and good record keeping provide a special insight and a special point of view. New statistical studies have recently been made to try to isolate the melanoma mechanism, and identify special risk factors. Statistics are indispensible in this effort because of the overpowering number of variables.

9. Statistics in Precision Engineering Research

I had a very interesting discussion on the question of statistics in Precision Engineering research with Dr. Horst Kunzman, Chief of Dimensional Metrology at the PTB (Bureau of Standards) in West Germany, and Dr. Erwin Loewen of Bausch and Lomb, who is here today. Dr. Kunzman argued that statistics can be a valuable research tool. We all agreed on that point. Dr.

Loewen then reviewed his experience of 25 years in upgrading the accuracy of diffraction grating ruling machines. In case after case, the diagnosis of a problem and the development of a solution all depended on a "Sherlock Holmes" (famous fictional detective) approach. The powers of personal observation and deduction were the key to progress.

The moral of this story is that we should send all new Precision Engineers to the local police department for detective training!

References

1. T. K. W. Althin, "C. E. Johannson - 1864-1943 - Master of Measurement, Nordisk Rotogravyr, Stockholm, 1948.

2. F. H. Rolt, "Gauges and Fine Measurements," Vol. I, II, McMillian and Co., London, 1929, (Available from University Microfilms, Ann Arbor, Michigan).

3. J. Loxham, "The Commercial Value of Investigations into Repeatability," Cranfield Unit for Precision Engineering, Bedford, England, (1970), (unpublished).

4. R. Gomory, "Technology Development" Science Magazine, Vol. 220, May, 1983.

5. J. Loxham, private communication.

6. NMTBA, "Definition and Evaluation of Accuracy and Repeatability for Numerically Controlled Machine Tools," Nat'l Machine Tool Builders Assoc., McLean, Virginia, 1972.

7. CIRP, "A Proposal for Defining and Specifying the Dimensional Uncertainty of Multi-Axis Measuring Machines," CIRP, Vol.27/2/, 1978.

8. R. R. Donaldson, "The Deterministic Approach to Machining Accuracy," Proc. Society of Manufacturing Engineers Symposium, Golden, Colorado, Nov. 1972.

9. J. B. Bryan, E. G. Loewen, "The Limit of Accuracy of Machine Tools," International Conference on Production Engineering, Aug. 26-29, 1974, Tokyo, Japan.

10. J. B. Bryan, R. R. Donaldson, E. R. McClure, R. W. Clouser, "A Practical Solution to the Thermal Stability Problem in Machine Tools," Society of Manufacturing Engineers Rept. MR72-138 (1972).

11. D. Halliday, R. Resnick, "Physics for Students of Science and Engineering," John Wiley & Sons, New York, pg. 552.

12. J. B. Bryan, "The Brute Strength Approach to Precision Engineering" - Precision Engineering - October, 1980, Vol. 2, No. 4, Jan. 1981, Vol. 3, No. 1.

13. J. B. Bryan, "Design and Construction of an 84" Diameter Diamond Turning Machine," Precision Engineering, January, 1979, Vol. No. 1.

14. J. B. Bryan, E. R. McClure, W. Brewer, J. W. Pearson, "Thermal Effects in Dimensional Metrology," ASME Production Engineering Conference Rept. 65-PROD-13 (1965).

15. J. B. Bryan, "International Status of Thermal Error Research, CIRP, 1968, Vol. XVI, pg. 203.

16. N. Taniguchi, "Current Status in and Future Trends of Ultraprecision Machining and Ultrafine Materials Processing," CIRP - Vol. 21/2/ 1983.

17. J. Loxham "Presidents Evening" Quality Engineer, May, 1972, Vol. 36, No. 5.

Auspices

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.